In-Space Propulsion
Connectivity To In-Space Fabrication and Repair

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Presented By

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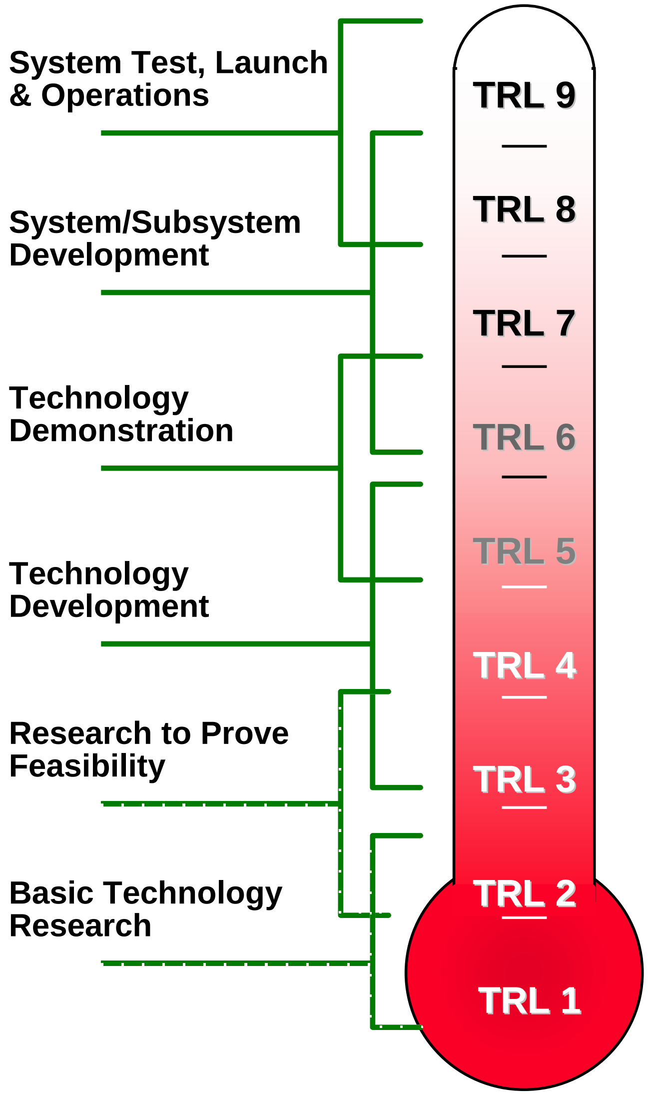
In Space Propulsion Program Overview

In-Space Propulsion Program Objective:

To develop in-space propulsion technologies that can enable and/or benefit near and mid-term NASA missions by significantly reducing cost, mass, and/or travel times.

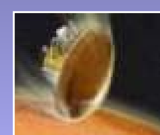
In-Space Propulsion Program Will Advance Mid-TRL Technologies to Support NASA Mission Applications



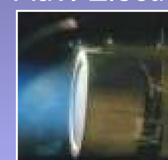
NASA Implementation: (Deep Space One Ion Engine Example)

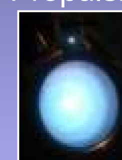
In-Space Propulsion Technologies

Aerocapture



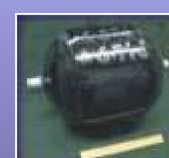
Adv. Electric Propulsion





Solar Thermal

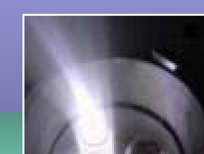
Adv. Chemical



Tethers

Solar Sails

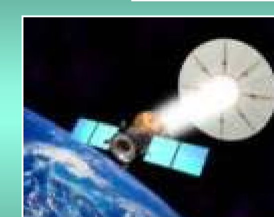
Plasma Sails



Low-TRL Technologies For the Future

External Pulsed Plasma

Fusion & Antimatter



Beamed Energy

In-Space Propulsion Technology Products

High Priority Technologies

- **Aerocapture**
  - Low-mass aeroshell with integrated TPS; Aerocapture flight-like instrumentation; Advanced Aerodynamic Decelerators (trailing ballutes, attached ballutes and inflatable aeroshells)
- **Next Generation Ion Thruster**
  - Next generation integrated ion engine thruster technology; NASA's Evolutionary Xenon Thruster; Carbon Based Ion Optics
- **Solar Sails**
  - Sail subsystem design and fabrication and ground demonstration; Structural testing of sail booms; Long term environmental evaluation of ultra-thin sail material

Medium Priority Technologies

- **Advanced Chemical**
  - Fuels development; Cryogenic Fluid Management; Lightweight components
- **kW Solar Electric Propulsion**
  - Laboratory demonstration of 50kW Hall thrusters; Competitively select thruster technology advancement based on application
- **Solar Thermal Propulsion**
  - Technology investments under further study; Directed tasks focused toward fundamental performance questions

High Risk/High Payoff & Lower Priority Technologies

- **Plasma Sails**
  - TBD
- **Momentum Exchange Tethers**
  - Model development and evaluation; Catch Mechanism concept; High strength tether
- **Solar Sails < 1g/m2**
  - Ultra-lightweight sail materials; Large area lightweight structures and mechanisms

In Space Propulsion
In Space Fabrication and Repair

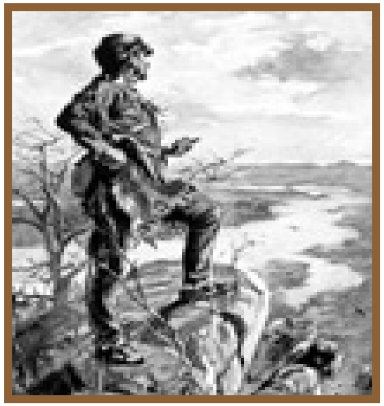
An Historical Perspective

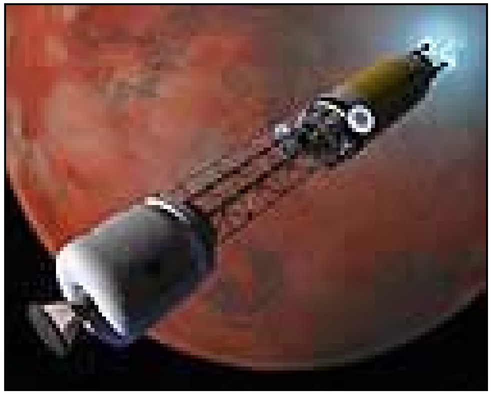
Historical Perspective

- We are building canoes for Lewis and Clark

Any study of the journey into the frontier of the West throughout the 1800's surely begins with the journey of Lewis and Clark and their Corps of Discovery at the beginning of that century. This journey, the first overland expedition to the Pacific Coast of this country and back, had many purposes: of commerce and transportation, as well as of exploration and scientific discovery.

<u>The In-Space Propulsion Program</u> seeks to provide enabling technologies to the expeditions of near- and mid-term NASA missions into the frontier of Solar System destinations.





Historical Perspective, Continued

♦ The Next 50 years -- Conestoga wagons, Prairie Schooners . . .

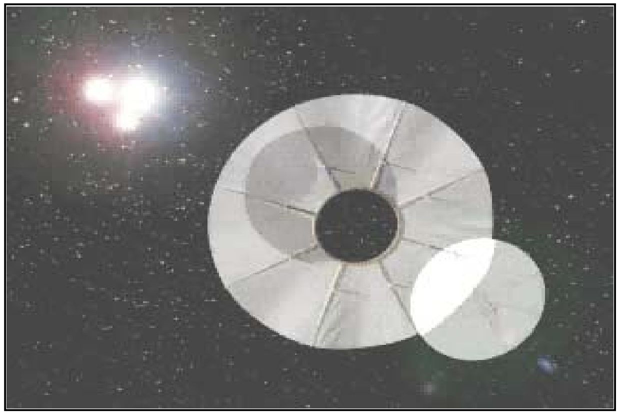
The Conestoga wagon was developed in the 1700's. Able to carry up to 5 tons, the bottom of the wagon curved up at both ends to prevent heavy loads from shifting. These wagons were the primary freight carriers before the introduction of the railroad.

They were adapted to the Sante Fe Trail with oxen or mules taking the place of horses, as better suited to the distance and environment.

The Conestoga was adapted once again for the journey west on the Oregon Trail. The Prairie Schooner was a smaller, lighter version, better suited for crossing streams and traveling over rough trails, as well as easier for a team to pull over long distances.

The Conestoga stands as a symbol not only of the pioneer spirit, but also of the necessity for methods of transportation to adapt to the frontier

<u>Over the next 50 years</u>, In-Space Propulsion will continue to select the technologies for advancement that will be best suited for future destinations, and enhancing/enabling for In Space Manufacturing and Repair.

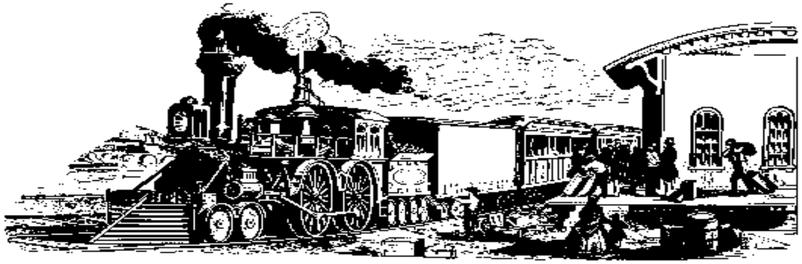


Historical Perspective, Continued

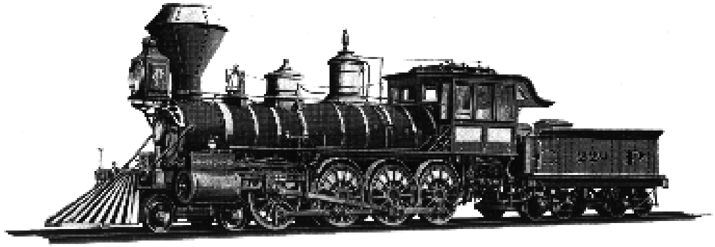
. . . and railroads

The expansion of the railroads increased the ease of travel and communication and encouraged even more westward expansion, both by settlers and industry. Throughout the West, many of the cities that thrive into the present began as settlements built where the railroad was expected to pass, and survived the difficult early stages of development because of the dependable influx of goods and people from the East.

Into the next half-century, putting in place the transportation nodes and manufacturing infrastructure to maintain In-Space Fabrication and Repair will be vital, and In-Space Propulsion technologies will be enabling for this task.



<u>In Space Propulsion</u> will lay the groundwork for reusable 'railroads' in space



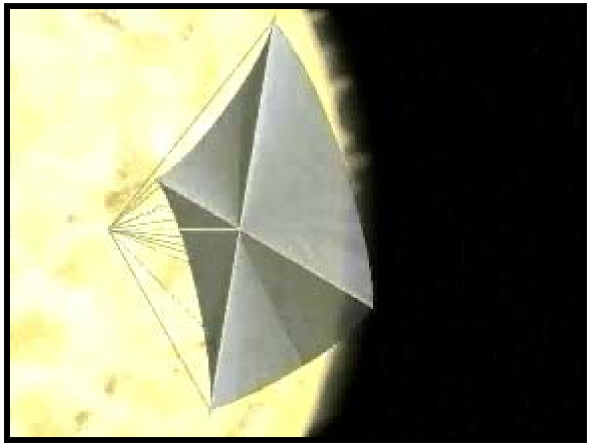
History Provides Many Apt Analogies

♦ Use Local Materials

- **Regolith for radiation shielding**
- **Water ice at destination utilized to produce fuel, oxygen, drinking water.**
- **Minerals mining for fabrication and energy source**

♦ Live off the Land

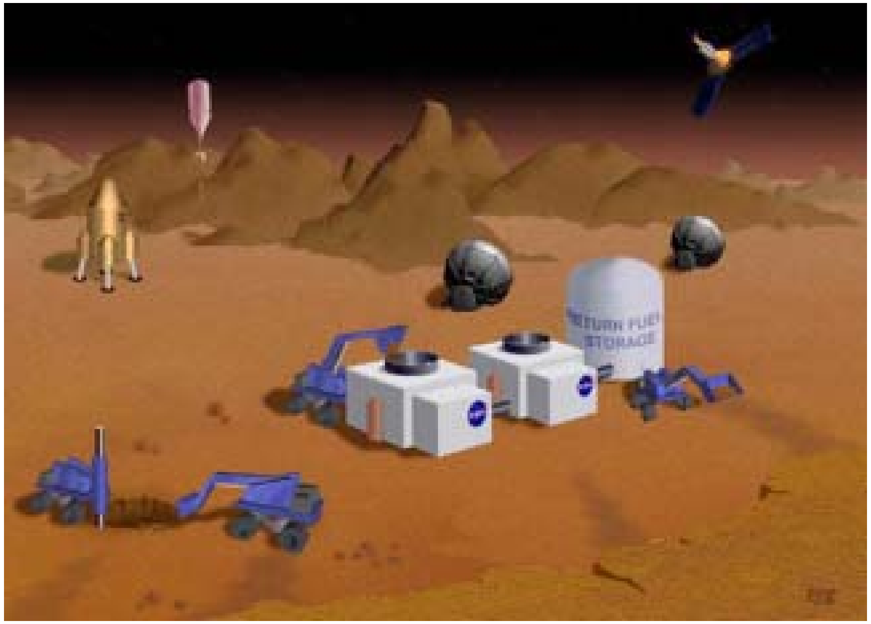
- **Sunlight (solar power and sails)**
- **Solar Wind (plasma sails)**
- **Earth's Ionosphere and Magnetic Field (Electrodynamic Tethers)**



How In-Space Propulsion Can Support In-Space Fabrication and Repair "Living Off The Land"

In Situ Resource Utilization

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)

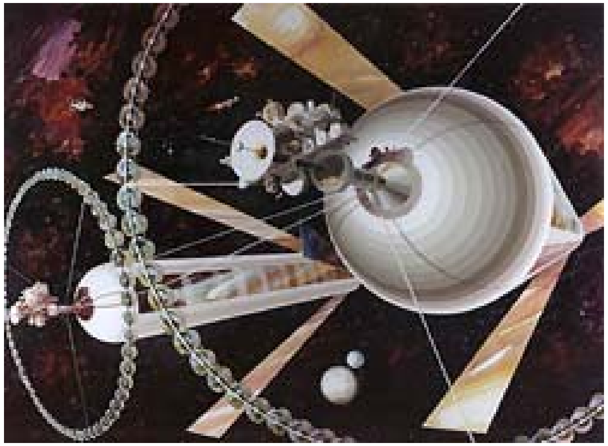


Using a portable laboratory, future robotic missions to Mars could breakdown gases from the atmosphere or process chemicals from the soil to manufacture fuel. This would be used as a propellant to return sample materials to Earth for analysis. A similar technology could derive oxygen and other gases from the atmosphere, to aid future missions by astronauts on visits to remote Martian outposts. Credit: NASA/JPL

- **Propellant can be manufactured in space (on another planet), reducing the need for resupply from Earth**
  - Reduced cost
  - Increased autonomy
- **Propellants that can be manufactured:**
  - **Mars** For immediate propellant needs, H_2 combined with the CO_2 from the Martian atmosphere (which is 95% CO_2) may be used to create an Oxygen-Methane bipropellant mixture.
  - **Moon** Hydrogen and Oxygen from lunar ice can be used for propellant.

Reboost / Drag Makeup of Orbital Manufacturing Facilities (Solar Electric Propulsion)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)

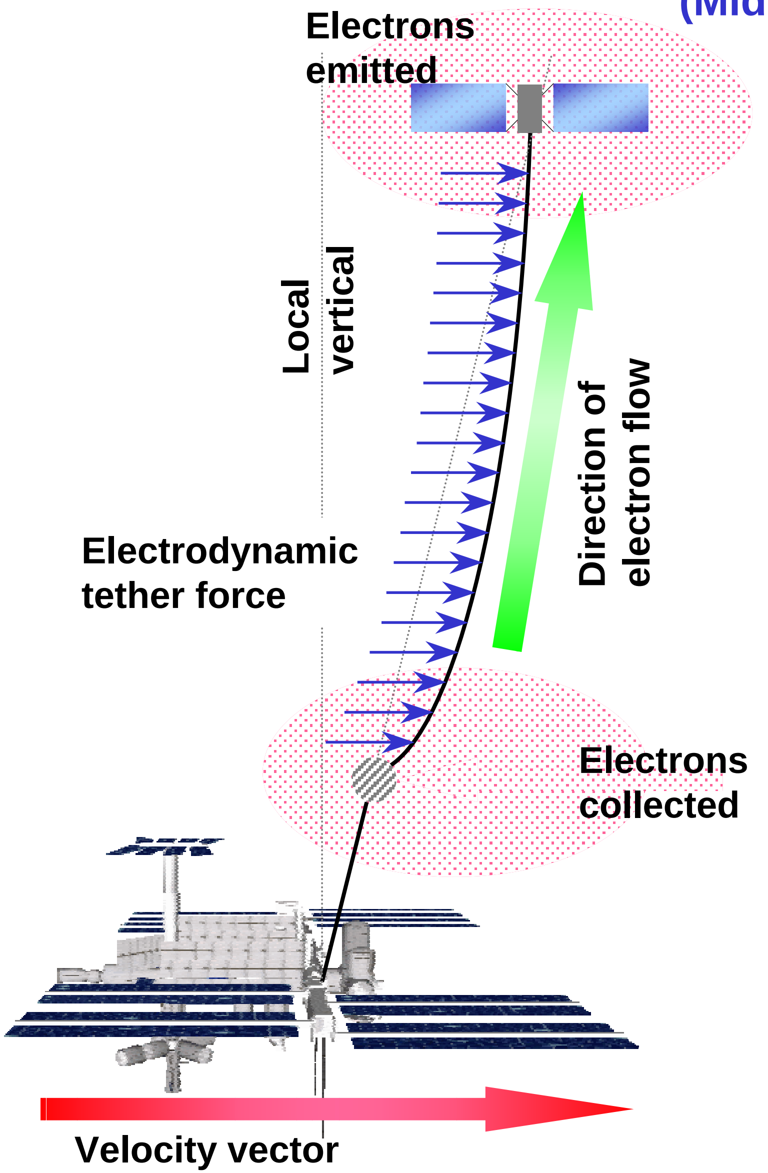


As envisioned by Gerald O'Neil, orbiting space habitats and fabrication facilities will require highly efficient propulsion that minimizes the need for re-supply from Earth.

- **Highly efficient solar electric thrusters can maintain spacecraft in LEO more cost effectively than with conventional chemical propulsion**

Reboost / Drag Makeup of Orbital Manufacturing Facilities (Electrodynamic Tethers)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)



- **Using the environment of LEO, large facilities can be reboosted electrodynamically, requiring no propellant or resupply**
  - F = I dL **X** B
    - – F = Thrust Force
    - – I = Current extracted from the ionosphere
    - – L = Length of conducting tether
    - – B = Earth's magnetic field

Highly Efficient Inter-Orbit Transfer (MXER Tethers)

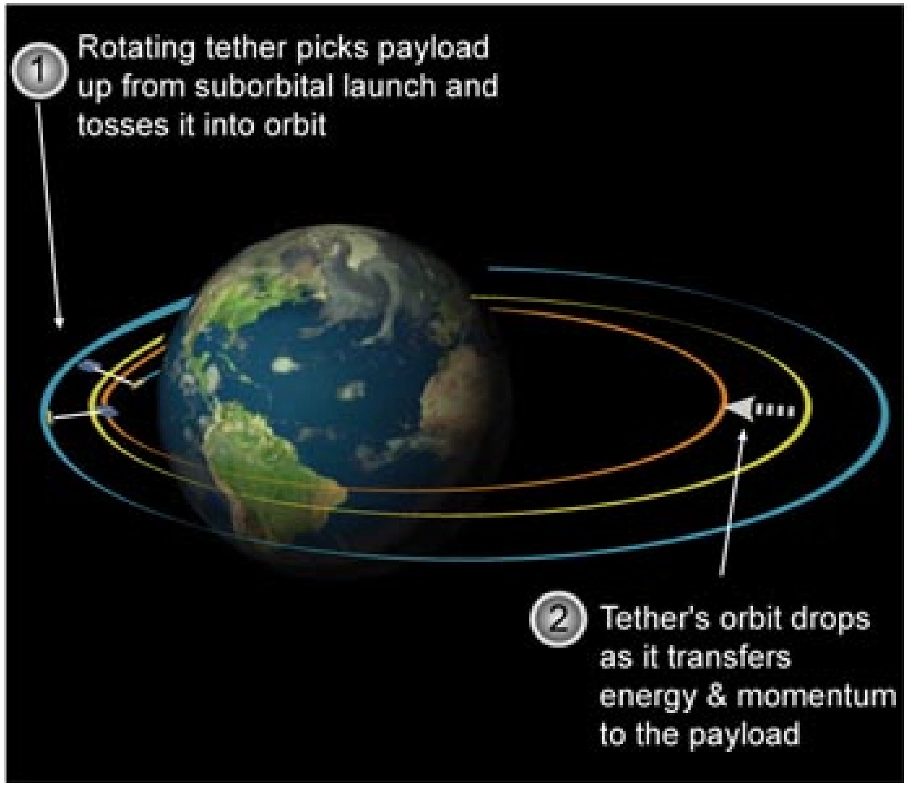
How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid-Term)

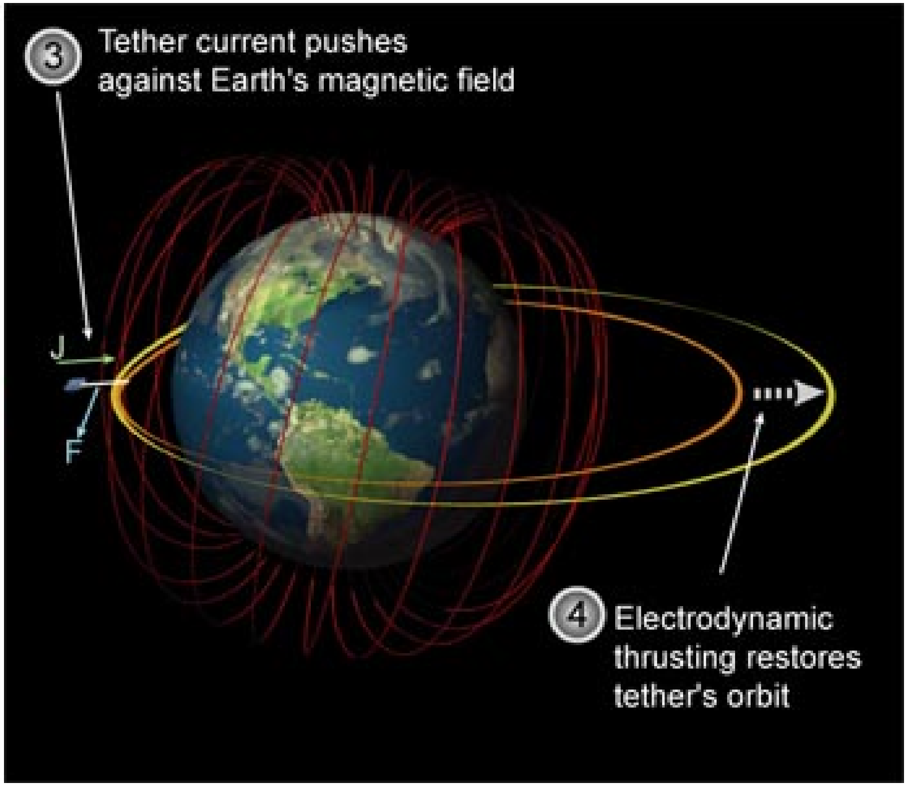
Momentum-Exchange/Electrodynamic-Reboost (MXER) tether systems can provide propellantless propulsion for a wide range of missions, including: orbital maneuvering and stationkeeping within Low Earth Orbit (LEO); orbital transfer of payloads from LEO to GEO, the Moon, and Mars; and eventually even Earth-to-Orbit (ETO) launch assist. By eliminating the need for propellant for in-space propulsion, MXER tethers can enable payloads to be launched on much smaller launch vehicles, resulting in order-of-magnitude reductions in launch costs.

- **Using a network of Momentum Exchange Tethers, large mass payload transfer within the Earth/Moon system may become practical**
  - A long, thin, high-strength cable is deployed in orbit and set into rotation around a central body.
  - The tether facility is placed in an elliptical orbit and its rotation is timed so that the tether is oriented vertically below the central body and swinging backwards when the facility reaches perigee
  - A grapple assembly located at the tether tip can rendezvous with and capture a payload moving in a lower orbit.
  - Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit.

Highly Efficient Inter-Orbit Transfer (MXER Tethers, Continued)

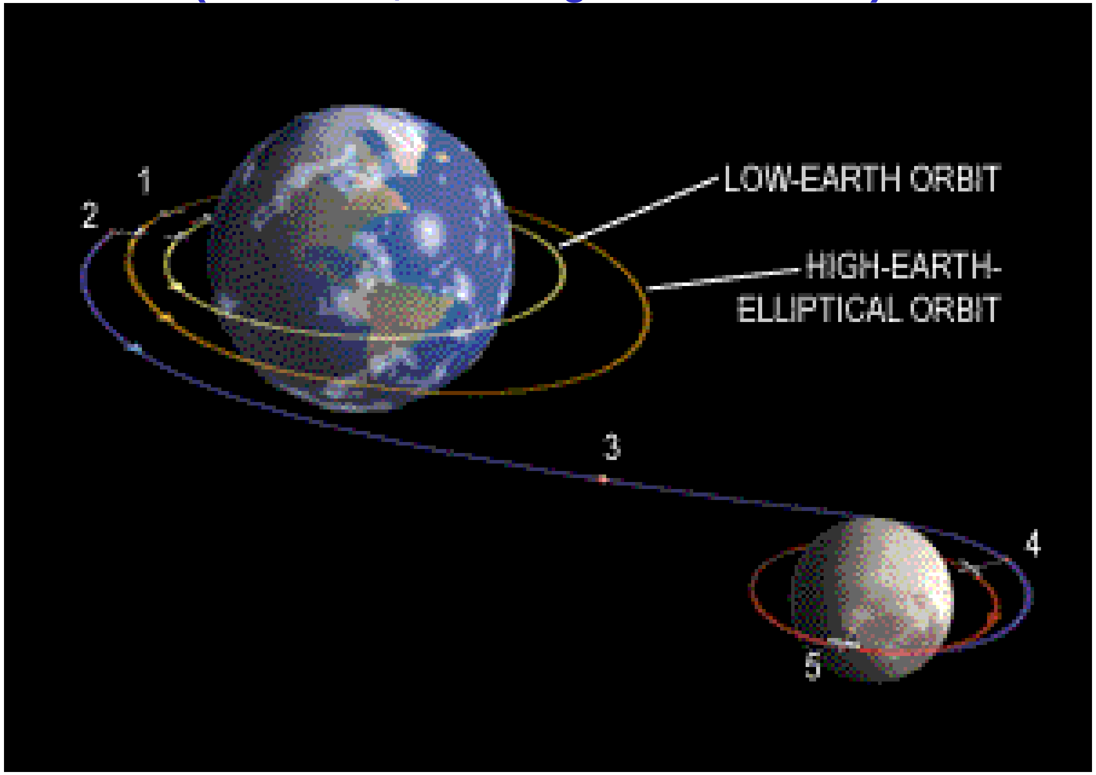
How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid-Term)





Highly Efficient Inter-Orbit Transfer (MXER Tethers, Continued)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far-Term; Building the 'Railroad')



LUNAR PAYLOADS could be delivered with a system of three tethers. The package is launched from Earth and is picked up by a tether in low orbit (*below*). This cartwheeling tether hands off the payload to another cartwheeling tether that is in higher orbit (*1*). Like a hunter hurling a rock with a sling, the second tether catapults the payload (*2*) toward the moon (*3*), where it is picked up by another tether in orbit there (*4*). This third cartwheeling tether then deposits the package <u>onto the moon's surface or picks up a payload for the return trip</u> (*5*).

Highly Efficient Inter-Orbit Transfer (Solar Thermal Propulsion)

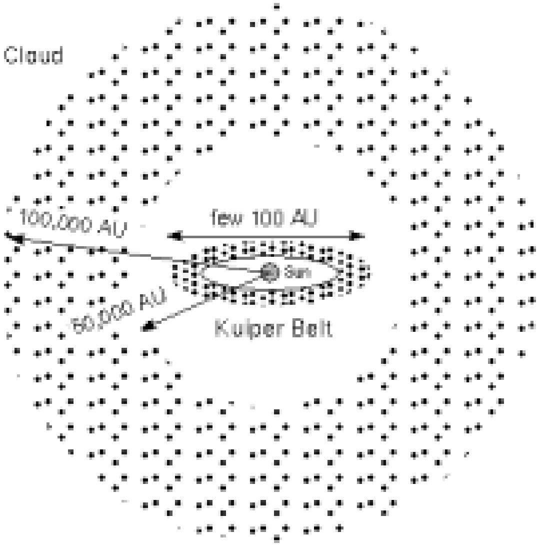
How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid Term)

In a solar/laser thermal rocket, solar or laser light is collected and focused to heat a propellant working fluid such as hydrogen. The collector mirrors are silvered balloon-like inflatable structures or thin sheets of silvered plastic supported by lightweight inflatable trusses. The light passes through a high temperature quartz window or into an open cavity on the side of the engine and focuses to a point to either directly heat the hydrogen propellant or heat a material such as graphite which then heats the hydrogen propellant.

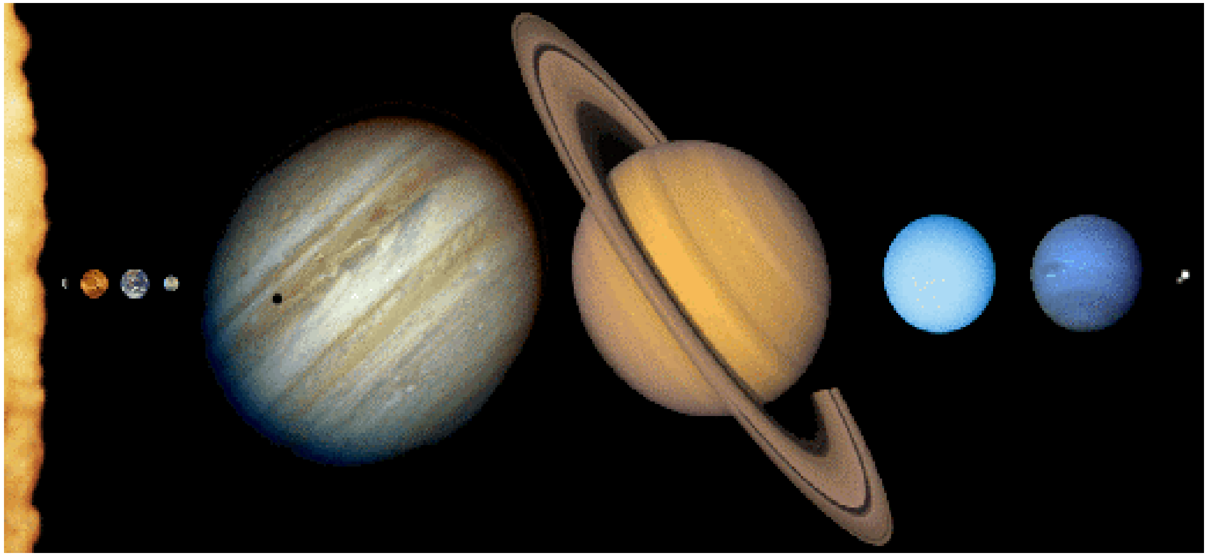
- **The energy of the sun can be focused to heat propellant for an in-space transportation system OR to drive an in-space furnace for large-scale manufacturing**

Deep Space Resource Surveys

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far Term)



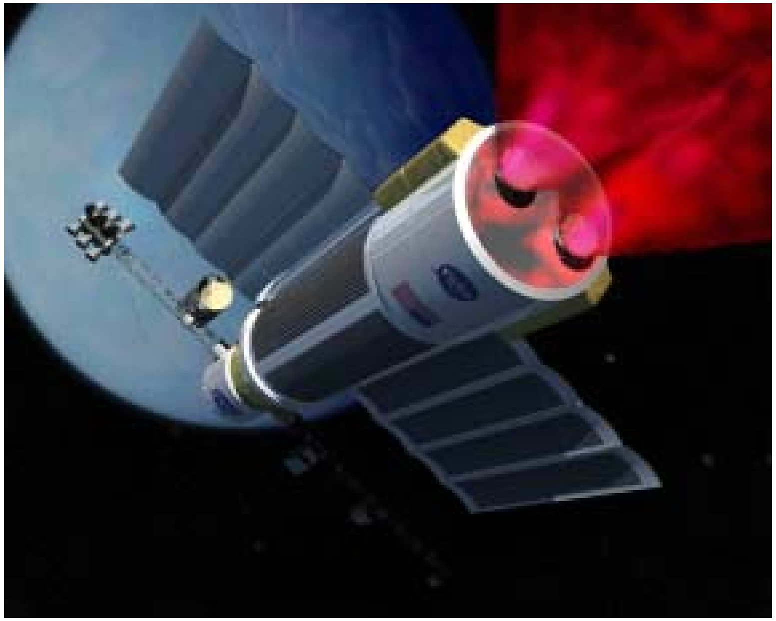
The Oort Cloud and Kuiper Belt (not to scale!). Extent of the two comet reservoirs are indicated. The nearest star is almost three times farther out than the Oort Cloud.



- **Highly energetic propulsion systems will be required to open the solar system economically**
  - We will need to move people and cargo across vast distances safely, quickly and efficiently
- **Potential destinations to be surveyed and utilized include:**
  - Asteroids and near-Earth objects
  - Kuiper Belt objects
  - Oort Cloud objects

Deep Space Resource Surveys (Antimatter Propulsion)

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far Term)



- **Harnessing the energy released when matter and antimatter meet is the key to being able to go "anywhere, anytime"**

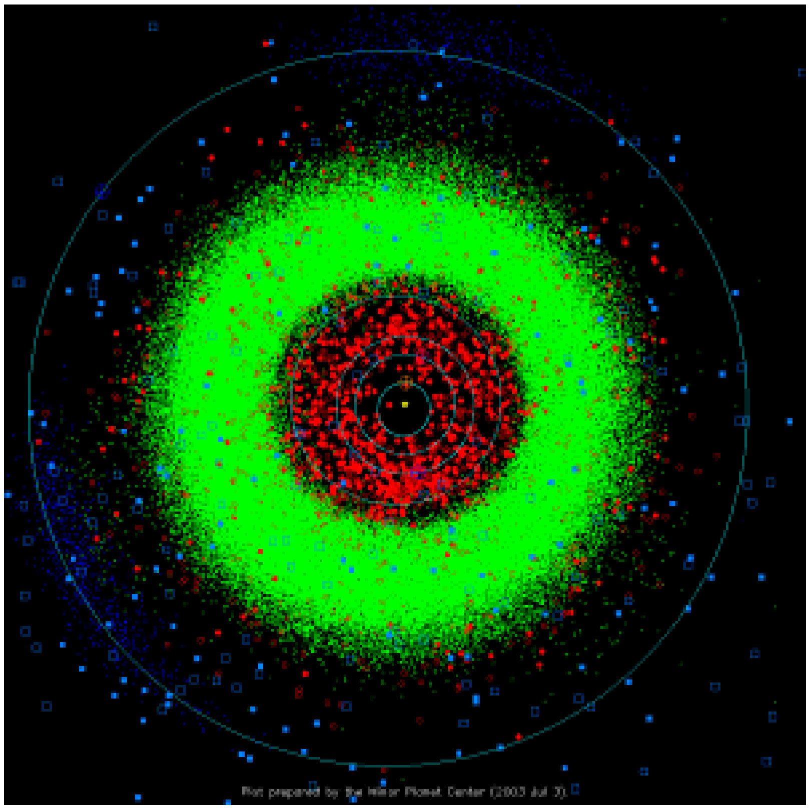
Propulsion Type	Specific Impulse [sec]	Thrust-to-Weight Ratio
Chemical Bipropellant	200 - 410	.1 - 10
Electromagnetic	1200 - 5000	10^{-4} - 10^{-3}
Nuclear Fission	500 - 3000	.01 - 10
Nuclear Fusion	10^{+4} - 10^{+5}	10^{-5} - 10^{-2}
Antimatter Annihilation	10^{+3} - 10^{+6}	10^{-3} - 1

Upon annihilation with matter, antimatter offers the highest energy density of any material currently found on Earth. Antimatter offers the greatest specific impulse of any propellant currently available or in development, and its thrust-to-weight ratio is still comparable with that of chemical propulsion. Simply put, it would take only 100 milligrams of antimatter to equal the propulsive energy of the Space Shuttle.

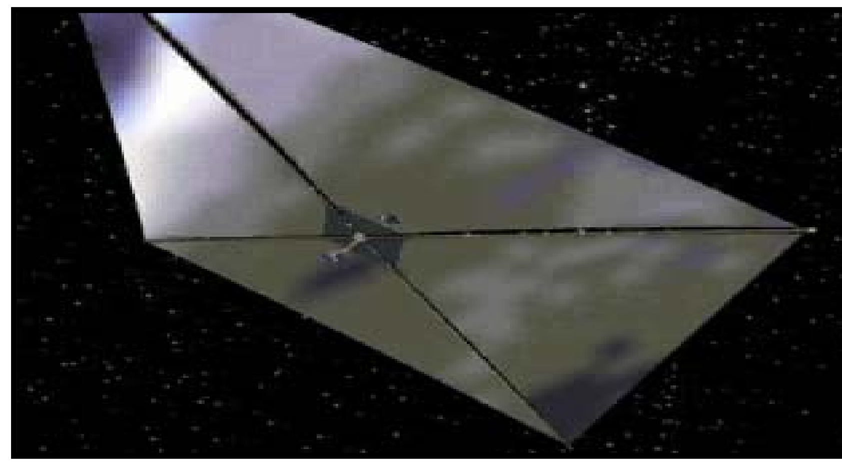
- **Unfortunately, though antimatter is real, we are far from being able to do this…**

Deep Space Resources
Bringing the Bounty Back Home

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Far Term)



- **Large, low-thrust solar sails could alter the orbit of resource-rich asteroids and divert them to near-Earth space for mining**

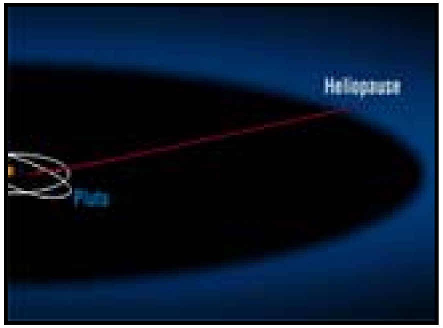


The orbits of the major planets are shown in light blue. The locations of the minor planets, including numbered and multiple-apparition/long-arc unnumbered objects, are indicated by green circles. Objects with perihelia within 1.3 AU are shown by red circles. Objects observed at more than one opposition are indicated by filled circles, objects seen at only one opposition are indicated by outline circles. The two "clouds" of objects 60° ahead and behind Jupiter (and at or near Jupiter's distance from the sun) are Jupiter Trojans, here colored deep blue. Numbered periodic comets are shown as filled light-blue squares. Other comets are shown as unfilled light-blue squares.

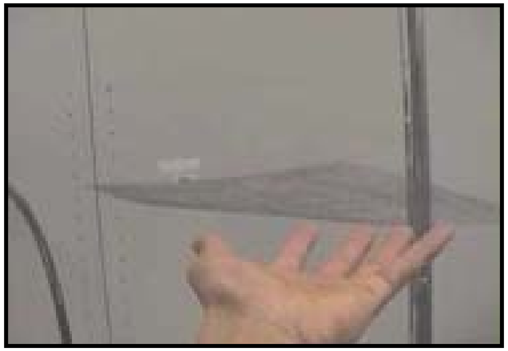
How In-Space Fabrication Can Support The Next Generation of In-Space Propulsion

Large Solar Sails for Interstellar Exploration

How In-Space Fabrication Can Support The Next Generation of In-Space Propulsion



The Heliopause is a barrier which charged particles from the sun cannot go beyond because cosmic rays from deep space force them back.

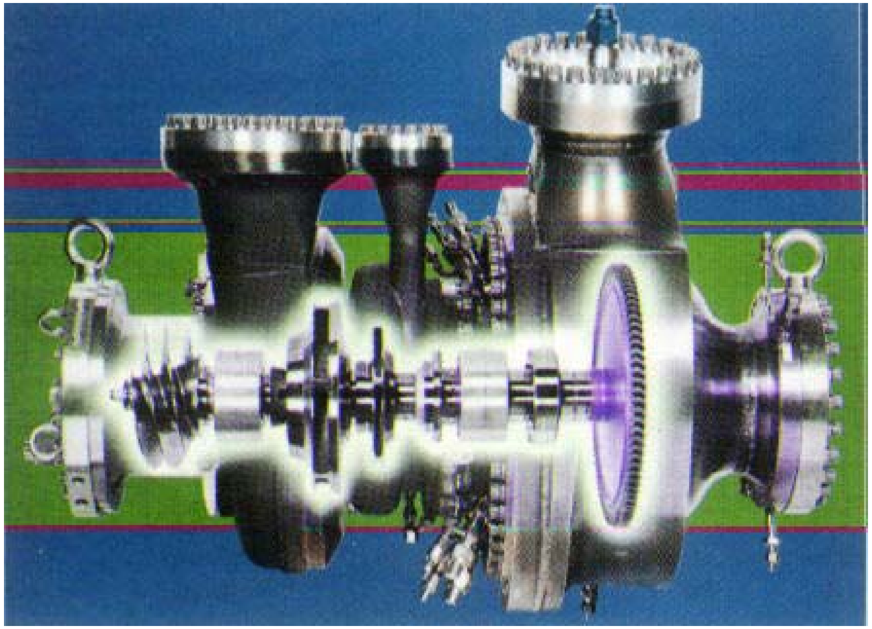


Carbon fiber μ-truss fabric (1 gm/m^2, 2 mm thick)

- **Solar sails use solar photon "pressure" or force on a thin, lightweight reflective sheet to produce thrust**
- **Sails with diameters >200m are required to propel spacecraft beyond the edge of the solar system (with reasonable trip times!)**
- **Large (> 200m), light-weight sails (<<1 gm/m^2) cannot be built and launched from Earth**
- **Manufacturing them in space provides an alternative**
  - Carbon spun sails
  - Chemical vapor deposition
  - Other???

Rapid Prototyping and Fabrication Using *In-Situ* Resources

How In-Space Fabrication Can Support The Next Generation of In-Space Propulsion



- **Using lunar regolith, it ought to be possible to rapidly cast high-temperature, high-strength components for propulsion systems**

Providing A Space Dock For the Star Ships…